High SBS-threshold, narrowband, erbium co-doped with ytterbium fiber amplifier pulses frequency-doubled to 770 nm

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Abstract: We present results of pulsed, narrowband amplification at 1540.6nm using a polarization maintaining, large mode area gain fiber co-doped with erbium and ytterbium. At a repetition rate of 55 kHz, 2.9 W of average 1540.6nm power were generated with a pulse duration of 136 ns, corresponding to an SBS free peak power of 360 W. The amplified signal was frequency doubled in peridically poled potassium titanyl phosphate and conversion efficiencies of up to 56% were generated. When varying the repetition rate between 55-150 kHz the conversion efficiency changed from 56% to 35% due to the limited pump power.

OCIS codes: (140.3570) Lasers, single-mode; (140.3280) Laser amplifiers; (140.3500) Lasers, erbium, (190.4370) Nonlinear optics, fibers, (190.2620), Frequency conversion, (290.5830) Scattering, Brillouin

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1. Introduction

NASA's Goddard Space Flight Center is investigating a number of remote sensing concepts using fiber lasers [1] including spectroscopic instruments using absorption lines of carbon dioxide [2] at 1570 nm and oxygen [3] at 770 nm. An L-band erbium-doped fiber amplifier (EDFA) or frequency-doubled C-band EDFA can reach the spectral regions of interest so NASA has been researching this technology. Fiber sources have the advantage of being rugged, reliable, compact, lightweight and efficient - making them suitable for many applications. In addition, the fiber gain media are ideal in many respects for spectroscopic applications because the glass host allows a much broader gain spectrum than a crystalline host, allowing a fiber system to reach a broader range of wavelengths.

For spectroscopic absorption linewidths in the range of a few GHz, high precision (fractions of a percent) measurement of the lineshape and strength is possible with a laser whose linewidth and stability is tens of MHz or less. This means that a transform limited, pulsed laser must have greater than ~100 ns pulsewidth to have sufficiently narrow linewidth. In addition, for remote sensing applications, the laser source must be power scalable and single spatial mode so that sufficient power can reach the desired target.

High peak optical power, single spatial mode and very narrow spectral width have been difficult to achieve simultaneously in fiber amplifiers due to limitations primarily from non-linear effects. The combination of high power, small cross section and relatively long interaction length found in fiber systems can lead to low thresholds for nonlinear effects. In general, the amplification of narrowband pulses is limited by SBS [4]. Standard techniques for increasing SBS threshold usually focus on increasing spatial mode size or decreasing effective interaction length. A common means of increasing the core size and maintaining single spatial mode behavior involves coiling a large mode area (LMA) fiber to increase loss of higher order modes [5]. However, coiling can cause mode deformations leading to a reduced mode field diameter [6]. Options for decreasing interaction length include shortening pulse width, decreasing fiber length and increasing spectral width (i.e. decreasing coherence length). Other SBS mitigation methods include using a temperature gradient [6,7] or strain gradient [8,9] to alter the SBS spectrum along the fiber (which essentially shortens interaction length). Acoustic mode shaping in the fiber design has also been explored to reduce the Brillouin gain [10-12]. However, up to now to our knowledge, no results on pulsed, high-peak-power, narrowband fiber sources have been published.

In this paper, we investigate the SBS threshold of 5 m polarization maintaining, gain fiber with 25-µm core diameter. Assuming a full-width at half maximum (FWHM) Brillouin linewidth, $\Delta\nu_{SBS}$=13MHz at 1.5 µm, the dephasing time, T_2=20 ns, can be calculated from the relation $T_2 = 1/(\pi\Delta\nu_{SBS})$. T_2 describes the required time to phase the created phonons, which establishes the macroscopic acoustic wave in the material. For pulsewidths less than T_2, the SBS gain is significantly reduced. As the pulse duration in this work is from 100-200 ns, the applied pulses are significantly longer than T_2 and consequently, the amplification experiments were SBS limited.

Since the SBS threshold is proportional [4] to the ratio of the mode field diameter divided by the length of the fiber, the SBS threshold can be increased by maximizing the fiber diameter and minimizing the fiber length. The maximum core diameter is limited by the required diffraction limited beam quality to ensure stable polarization maintaining performance of the power amplifier, which is crucial for stable frequency conversion. The erbium, ytterbium co-doped fiber, which was used in this work has a core numerical aperture (NA) of 0.1 with a core diameter of 25 µm. The low core NA is due to a germanium doped pedestal around the core. With such a low core NA, diffraction limited beam quality can be easily achieved by proper mode matching and coiling of the gain fiber [5]. The stress rods required to induce birefringence in the fiber are located in the double cladding of the gain fiber, which has a diameter of 300 µm. The NA of the pump cladding is 0.48, which is attained with a low index fluoroacrylate coating. For the given core composition and the particular core/cladding ratio, the cladding absorption at 915 nm is approximately 0.8 dB/m leading to a corresponding absorption of 2.4-3.2 dB/m at 977 nm, i.e. core absorption of 324-460 dB/m @977 nm while the absorption at 1535nm equals to 30 dB/m. To minimize the fiber length, the power amplifier was pumped at 977 nm.

2. Experimental setup and results

The experimental setup is shown in Fig. 1, whereby the all-fiber seed source for the power amplifier used in this work consists of a distributed feedback laser (DFBL) and two amplifier stages.

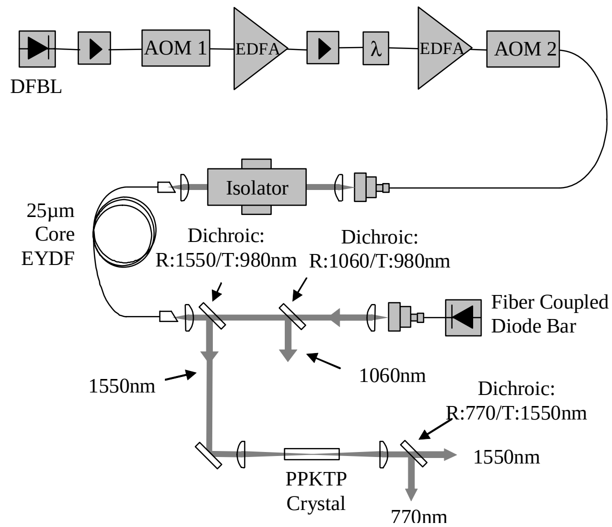

Fig. 1. Setup of polarization maintaining free space power amplifier used for narrowband amplification experiments. DFBL - distributed feedback laser, AOM - accousto optic modulator, EDFA – erbium doped fiber amplifier, PPKTP - peridically polled potassium titanyl phosphate, EYDF- erbium ytterbium doped fiber.

The DFBL was operated at 1540.6 nm in cw mode to guarantee narrow spectral linewidth, (i.e. 1 MHz FWHM). An isolator protected the DFBL from feedback originating in the following amplification stage. The DFBL was externally modulated by using an acousto-optic modulator (AOM), leading to a pulse train with 171 ns (FWHM) at 55 kHz and an average power of 144 µW. A low power, PM, EDFA was used to amplify the seed pulses. After a following isolator and amplified spontaneous emission (ASE) filter, approximately 2 mW at 55 kHz were available to seed the subsequent booster EDFA. To eliminate build-up of optical power emitted within the same bandwidth of the ASE filter, an additional AOM was used directly after the second EDFA to guarantee that all the seed power for the power amplifier was contained in the pulses. At the output of the second AOM, 40 mW were available at 55 kHz. Examples of temporal pulseshapes measured directly after the first AOM and after the second AOM are also shown in Fig. 2, whereby pulse steepening from 171ns to150ns is observed.

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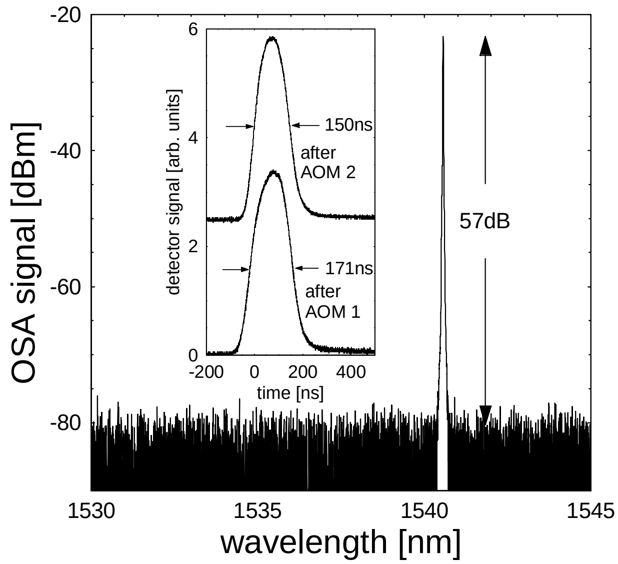

Fig. 2. Spectrum after second AOM (AOM2) recorded with a resolution of 0.01 nm. The signal bandwidth is smaller than the instrumental resolution as the pulses are transform limited, i.e. approximately 3.5 MHz (0.027 pm). Additionally, a temporal pulseshape of the externally modulated DFBL (after AOM1), and a temporal pulseshape after the second AOM (AOM2) are shown in the insert.

According to Fig. 2, no broadband ASE is observed in the spectrum after the second AOM and approximately 57dB signal to noise ratio is measured between the signal and the noise floor. The actual spectral lineshape can't be resolved, as the signal is narrower than the OSA resolution.

After the second AOM, free space optical components were used for the PM power amplifier. A free space isolator placed between the second AOM and power amplifier protected the second PM-EDFA from feedback generated by SBS in the power amplifier. To achieve diffraction limited beam quality from the power amplifier, the seed light was mode matched to the fundamental mode of the gain fiber, which has a mode field diameter of 20 µm. The gain fiber had a length of 5 m and was pumped in a counter propagating scheme with a fiber coupled pump diode emitting a maximum pump power of 30 W at 977 nm from a 200 µm core diameter with NA=0.22. The counter-propagating scheme is utilized to minimize the nonlinear interaction length for SBS within the fiber. Also as mentioned earlier, the gain fiber was pumped at 977 nm to minimize the fiber length, as the absorption at 977 nm is approximately 3-4 times higher than at 915 nm. The pump light was coupled into the double cladding of the gain fiber by using a telescope with a magnification of approximately 1. Between the two focusing lenses of the telescope, a dichroic optic, which is highly reflective at 1520-1700 nm (R>99%) and highly transmissive at 915-1180 nm (T>97%, T=99.5% at 1030 nm), was used to separate the amplified pulses from the pump diode light. An additional dichroic optic was placed into the collimated section of the telescope to separate the 1030 nm emission from the 977 nm pump light. This second dichroic was required to protect the pump diode from 1030 nm radiation, as the gain fiber emits up to 0.6 W at 1030 nm in the forward direction at maximum pump power. The 1030 nm emission is caused by non-optimized energy transfer between the ytterbium ions and the erbium ions in the gain fiber. Therefore, not all the energy stored in the ytterbium ions migrates to the erbium ions and is being emitted at 1.0 µm. The non-optimized energy transfer explains also the low conversion efficiency of approximately 10% of the gain fiber.

The spectrum of the 1541 nm pulses is shown in Fig. 3 when operating at an average power of 2.9 W at 55 kHz with AOM 2 included in the setup. The spectrum shows no significant out-of-band ASE within 1530-1550 nm. The additional insert on the left side in

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Fig. 3 shows the detail lineshape of the same spectrum without any measurable in-band ASE. The right insert shows a spectrum taken without AOM2 at the same average power and at 150kHz. The right insert illustrates a noticeable 0.5 nm wide ASE pedestal due to in-band ASE and also indicates broadband ASE as the noise level is approximately -75 dBm compared to -85 dBm of the right insert. The above results show that the extinction ratio of AOM1 was too low and therefore, a second AOM was required for the setup to ensure that all the energy is included in the pulses. The insert clearly displays that no in-band ASE is present within a 60 dB range relative to the peak of the amplified signal.

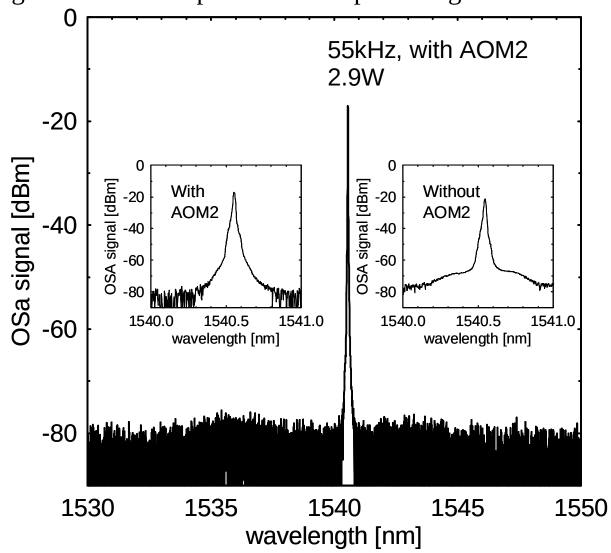

Fig. 3. 1.54 µm output spectrum at 55 kHz recorded with a 0.01 nm resolution and AOM2 included in setup. Left insert: detailed lineshape of 2.9 W, 55 kHz spectrum with AOM2 in setup. Right insert: Spectrum without AOM2 at 2.9 W and 150 kHz.

A plot of the average power at 1.54 µm as a function of pump power is shown in Fig. 4.

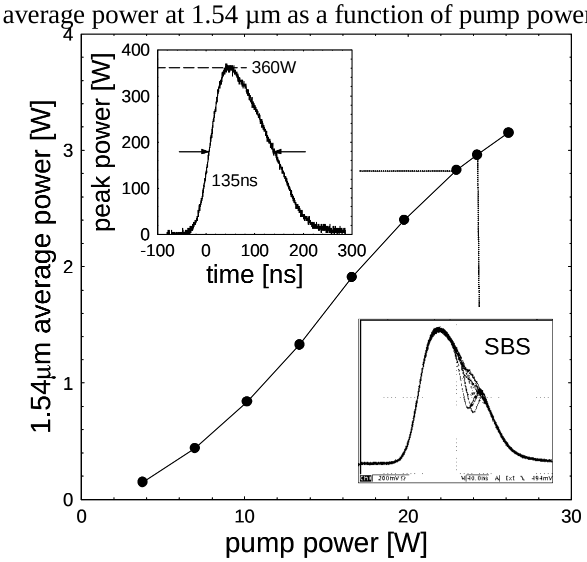

Fig. 4. 1.54 µm output power at 55 kHz as a function of applied pump power. Additionally, a temporal trace (upper left) with the maximum SBS free peak power and a (long persistence) oscilloscope trace (lower right) showing the onset of SBS are displayed in two separate inserts. The time base of the oscilloscope display was set to 40 ns/div.

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The highest achievable power without the presence of SBS was 2.9 W, i.e. 53 µJ per pulse, at 55 kHz. The pulse energy determination is based on the average power, as the spectra shown in Fig. 3 show no broad-band ASE as well as no in-band ASE. Preferably, the pulse energy would have been measured with a pyroelectric energy meter, however, to our knowledge no pyroelectric joule-meter is available for >20 kHz. A temporal pulse trace for 2.9W average power is also shown in the upper left corner of Fig. 4, whereby the peak power is plotted as a function of time. The temporal trace has a FWHM of 137 ns and is slightly asymmetric due to further pulse steepening in the power amplifier. When increasing the average power to 3.0 W at 55 kHz, SBS was observed. The onset of SBS was detected by the depletion in the temporal lineshape of the amplified signal due to SBS, which occurs in the falling trail of the amplified pulse and leads to a noticeable increase in the signal-to-noise ratio. Prior to the onset of SBS the pulse amplitude was very stable. As the pulse stability requirement is very critical for remote sensing applications, we used the depletion of the amplified pulses to detect SBS which leads to pulse instabilities, instead of recording the back-ward propagating SBS spectral signal. An example of a set of temporal pulse shapes is shown in the lower right corner of Fig. 4. The multiple overlapping traces were recorded by using a long persistence setting of the oscilloscope.

The 2.9 W average measurement corresponds to 360 W peak optical power and is the highest SBS-free, single frequency, single spatial mode, peak optical power reported for an EYDFA (known to the authors). Higher peak optical powers have been achieved with shorter pulses, wider spectrum or worse beam quality. The best previously reported SBS-free measurement in an EDFA is a CW measurement of 150 W [13].

The excellent waveguide properties of the gain fiber lead to a polarization extinction ratio of >20 dB and the measured beam quality was nearly diffraction limited, i.e. $M_x^2 = 1.03$ and $M_y^2 = 1.09$ for two orthogonal directions. The amplified pulse train was focused into a peridically poled potassium titanyl phosphate (PPKTP) crystal, whereby a crystal oven and a temperature controller were used to stabilize the crystal temperature to 150°C. After passing through the crystal, the frequency-doubled light was separated from the 1540.6 nm source and the conversion efficiency shown in Fig. 5 was determined by the ratio of the 1540.6 nm input power in front of the crystal and the generated 770.3 nm radiation.

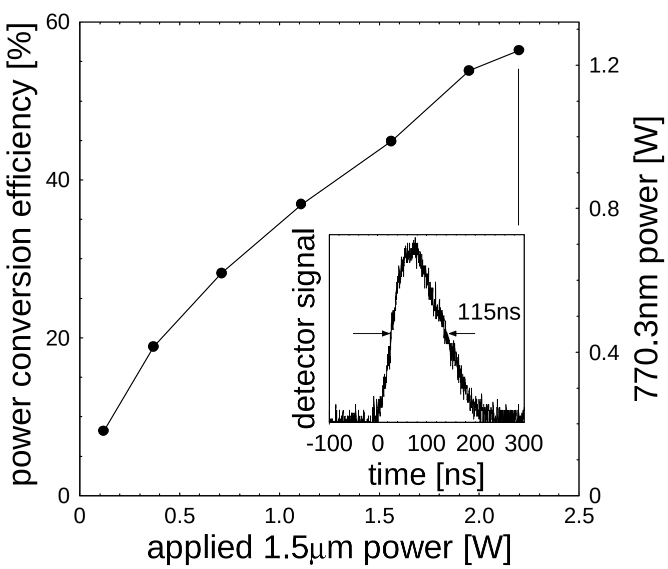

Fig. 5. Power conversion efficiency to 770.3 nm as a function of applied 1540.6 nm power. The insert shows a temporal trace of a 770.3 nm pulse at the highest conversion efficiency of 56%.

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Due to non AR-coated optics, 24% of the available fundamental power was lost for the conversion step. An example of a temporal lineshape of the frequency-doubled signal at 1.2 W average power is shown in the lower right corner of Fig. 5.

We also performed conversion experiments at different repetition rates as shown in Fig. 6.

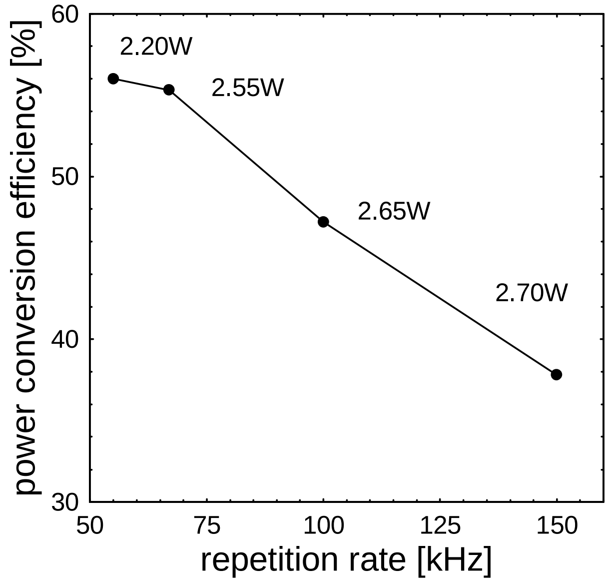

Fig. 6. Conversion efficiency as a function of repetition rate between 67 -150 kHz for fixed pump power of 29 W. Note: The pump power was limited to 29 W. The average power at 1540.6 nm is shown in the plot for the corresponding repetition rate. The insert shows an OSA spectrum recorded at 0.05nm resolution. Only minor ASE emission at 1525 nm is noticeable.

Due to the limited pump power, the achievable conversion efficiency was reduced at greater than 55 kHz. Nevertheless, the results in Fig. 6 show the flexibility of the fiber MOPA system, enabling the operation at different repetition rates.

3. Conclusion

We performed narrowband pulse amplification experiments using a polarization maintaining power amplifier pumped and seeded with free space optics and achieved an SBS free peak power of 360 W at 55 kHz with a pulse duration of 136 ns, which corresponds to 53 µJ/pulse and 2.9 W average power. The beam quality was nearly diffraction limited, i.e. $M_x^2 = 1.03$ and $M_y^2 = 1.09$ for two orthogonal directions, and a polarization extinction ratio of slightly better than 20 dB was achieved. The narrowband pulses were frequency-doubled using a PPKTP crystal. With the beam quality of the power amplifier output being nearly diffraction limited, the conversion efficiency reached 56% with an average input power of 2.2 W at 1540.6 nm. When varying the repetition rate between 55 kHz and 150 kHz the conversion efficiency varied between 56% to 37%, while keeping the pump power of the power amplifier constant at 29 W. An improved fiber with increased concentration of erbium and ytterbium ions is currently under development and we expect that he efficiency of the fiber will increase at least 2-times, i.e. >20%. With this improved fiber we expect to achieve an SBS threshold of >1 kW.

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